Agonist Contractions Against Electrically Stimulated Antagonists

Tojiro Yanagi, MD, Naoto Shiba, MD, Takashi Maeda, PT, Kiyohiko Iwasa, PT, Yuichi Umezù, MD, Yoshihiko Tagawa, PhD, Shigeaki Matsuo, PhD, Kensei Nagata, MD, Toshiyusu Yamamoto, PhD, Jeffrey R. Basford, MD, PhD


Objective: To assess an exercise program that uses electrically stimulated antagonists to resist agonist muscle contractions.

Design: In 1 limb, electrically stimulated antagonists resisted elbow flexion and extension. In the other, stimulation occurred without volitional muscle contraction.

Setting: A biomechanics laboratory in Japan.

Participants: Twelve men between the ages of 19 and 24 years. Subjects served as their own controls.

Intervention: Subjects trained 3 times a week for 12 weeks. Each session consisted of 10 sets of 10 elbow flexor and extensor contractions.

Main Outcome Measures: Isokinetic elbow extension and flexion torques. Biceps and triceps brachii cross-sectional areas increased in all muscles but were most marked in the antagonist muscles.

Results: Elbow extension torques increased (32.85% at 30°/s, 27.20% at 60°/s, 26.16% at 90°/s; all P<.02) over the training period in limbs that trained against electrically stimulated antagonists. Control limb extension torque increases were smaller (8.52%–14.91%) and did not reach statistical significance. Elbow flexion torques improved in both groups, but the changes did not reach statistical significance. Cross-sectional areas increased in all muscles but were most marked in the antagonist stimulated limbs: triceps 16.20% versus 4.25% (P<.01) and biceps 16.65% versus 7.00% (P=.005).

Conclusions: Exercises that use electrically stimulated antagonist muscles may be effective in increasing muscle strength and mass.

Key Words: Electric stimulation; Exercise; Muscles; Rehabilitation; Torque.

© 2003 by the American Congress of Rehabilitation Medicine and the American Academy of Physical Medicine and Rehabilitation

Neuromuscular electric stimulation (NMES) is widely used to lessen immobilization-associated muscle weakness, to strengthen muscles, and to improve function in people with neuromuscular disabilities.1-4 Although NMES has been in use for more than 40 years, its clinical value and optimal application remain controversial. However, several facts have been established. For example, research has found that NMES is effective in strengthening limb muscles after surgery.3,4 In addition, several researchers5-6 have found that the muscle strength of healthy subjects can be increased by 10% to 20% with 3 to 6 weeks of high-intensity stimulation.

NMES research typically focuses on the direct stimulation of the muscles to be exercised. Although this approach does produce strength gains,5-6 the gains are realized more slowly than patients would like. Also, the approach may be little more effective than traditional weight-based resistance training programs.5,6 An NMES program that could produce faster or larger gains in strength and muscle bulk than is possible with current approaches would be attractive.

The idea of using electric stimulation to provide the training resistance to a contracting muscle (much as a dumbbell provides resistance to the elbow flexors during an elbow curl) is particularly alluring. We, therefore, decided to turn the traditional NMES paradigm around and investigate a situation in which the antagonist of the muscle being exercised was stimulated. Specifically, we developed a hybrid strengthening technique that uses the force generated by an electrically stimulated antagonist to provide resistance to a volitionally contracting agonist. In other words, the agonist performs a volitional concentric contraction against an electrically stimulated antagonist (fig 1).

The purpose of this study was to compare the muscle strengthening and bulk increasing benefits of this hybrid approach with the benefits of a conventional NMES program.

METHODS

The study protocol was approved by the institutional review board of Kurume University. Informed consent to participate was obtained from 12 healthy right-hand dominant sedentary men. Subjects were required to have normal musculoskeletal examinations (ie, normal strength, sensation [light touch, sharp, proprioception], coordination, range of motion [ROM]). Hand dominance was determined in accordance with the Edinburgh Inventory.7 Subjects were block randomized into 2 groups of 6.

In 1 group, the hybrid exercise program was performed with the right upper extremities and a conventional NMES program was performed with the left. In the other group, the hybrid program was performed with the left upper extremities and the control program was performed with the right. Participants were not paid.

Exercise

Hybrid exercise. Subjects trained 3 times a week (Mondays, Wednesdays, Fridays) for 12 weeks. Each exercise session consisted of 10 sets of 10 reciprocal 2-second elbow flexion and extension contractions. Sets were separated by...
1-minute rest intervals, and an exercise session was completed in 15 minutes and 40 seconds. Exercises were performed in a standardized manner, with the biceps brachii stimulated as the subject volitionally extended his elbow and the triceps brachii stimulated as he volitionally flexed his elbow (see Electric Stimulation Protocol below). Joint ROM was measured with a goniometer and restricted to an arc that extended from 15° to 105° of elbow flexion. Subjects changed the direction of their joint movement when the stimulator emitted a tone (fig 2).

**Control exercise.** A similar program was followed with the control limb, except that the elbow was immobilized in a brace at 60° of flexion and the subject was instructed not to attempt a volitional muscle contraction.

**Electric Stimulation Protocol**

**Electric stimulation device.** The electric stimulation device was developed by this group and has been described previously. Briefly, it consists of a waveform generator and a microcomputer that delivers stimulating signals to as many as 8 individually controlled electrodes. Frequency, intensity, and waveform characteristics can be individually selected for each pair of electrodes. In this experiment, a pair of 2×6cm custom-made gel-coated silver fiber electrodes were placed over the motor points of the biceps and triceps brachii that had been isolated by moving a probe over the skin surface to find the lowest threshold for electric stimulation.

---

**Fig 1.** Schematic model of the exercise method. Note that both the volitionally activated agonist and the electrically stimulated antagonist contract during joint motion. The result is that both muscles are exercised and that a longitudinal compressive load is placed on the bone.
Fig 2. The subject exercises the left arm for the hybrid method and the right arm for the control method. Specially made gel-coated metal fiber electrodes are placed over the motor points of the biceps and triceps brachii. One pair of electrodes is placed over the each muscle of each upper limb. To avoid the influence of gravity, the subjects set their upper limbs onto the cushions, which have a 30° angular surface. The hybrid exercise is performed from 15° to 105° of flexion during elbow flexion and extension motion.

Stimulation waveform. A 5000Hz carrier frequency was modulated at 20Hz (2.4ms on, 47.6ms off) to deliver a rectangular waveform for 2-second intervals.

Stimulation intensity. The maximum comfortable intensity was determined at each session by increasing the stimulation voltage until the subjects reported discomfort. Mean voltage for NMES was 60.35±19.55V. Output powers were less than 10W, and the stimulation parameters included current intensities of less than 10mA/cm² and voltage less than 80V (fig 2).

Torque Measurements
Maximal isokinetic elbow flexion and extension torques were measured with a KIN-COM® dynamometer at a baseline immediately before the exercise trial began, as well as at the 6-week midpoint and 12-week conclusion of the exercise program. Subjects were tested at angular velocities of 30°, 60°, and 90°/s with their forearm in a neutral position while they sat in a chair with their shoulder and body fixed to a frame. The averages of 3 maximal elbow extension and flexion torque were used in calculations.

Measurement of Muscle Bulk
Biceps and triceps brachii cross-sectional areas (CSAs) were measured on the same days that the torque determinations were made (ie, at the baseline, middle, end of the exercise trial). A standardized procedure was followed. The position of the mid-point between the acromial process and medial epicondyle was marked with an indelible marker at the first session and renewed as necessary throughout the experiment. An adhesive 5×5×5mm daub of gel was placed on the mark at the time that CSA determinations were made, and scout views were used to ensure that the scanning position did not change between sessions. CSAs were measured on the display of a magnetic resonance imaging (MRI) device (Hitachi Airis II®) by a blinded observer. Changes in CSA with time were defined as the ratio of the change in CSA over the period studied divided by the baseline value, that is, CSA change = ([CSA at the midpoint or end of the exercise trial/CSA at baseline] − 1).

Statistics
Standard methods were used to calculate mean values and standard deviations. Torques at baseline were compared with torques found at the 6-week midpoint and at the 12-week conclusion of the exercise trial. CSA changes were compared at the same intervals. The F distribution and 2-tailed Student t-tests were used. P values of ≤ .05 were considered to be significant. Statistical analyses were performed with SPSS, version 8.0, for Windows.

RESULTS
The mean age of the participants was 21.5 years (range, 19–24y). All subjects attended all 36 sessions of the training program. There were no injuries, but a few individuals complained of postexercise delayed-onset muscle soreness early in the program.

Muscle Force Measurement: Elbow Extension Torque
Hybrid exercise. The maximal extension torques of the hybrid exercise group at baseline were 29.92±5.70Nm at 30°/s, 29.42±5.42Nm at 60°/s, and 28.67±5.31Nm at 90°/s. At the 6-week midpoint, these values had increased to 33.75±6.90Nm, 31.83±6.85Nm, and 30.33±7.14Nm, respectively. At completion of the 12-week training, these torques had further increased to 39.75±9.76Nm, 37.42±9.88Nm, and 36.17±9.83Nm. Although the increases in extension torque at 6 weeks did not reach statistical significance, the increases at 12 weeks were marked and statistically significant (32.85% at 30°/s, P = .007; 27.20% at 60°/s, P = .03; 26.16% at 90°/s, P = .02, respectively; fig 3A).

Control limbs. Maximum extension torques in the control limbs at baseline were 31.33±6.85Nm at 30°/s, 31.33±7.75Nm at 60°/s, and 30.08±7.35Nm at 90°/s. At the midpoint of the program, these values had increased to 35.5±6.23Nm, 33.58±5.07Nm, and 32.42±4.66Nm, respectively. Although these torques had further increased after 12 weeks (36.00±8.45Nm, 34.00±7.85Nm, 33.00±7.68Nm, respectively), neither the 6- nor 12-week changes were statistically significant (fig 3A).

Muscle Force Measurement: Elbow Flexion Torque
Hybrid exercise. Maximum flexion torques at baseline were 28.33±9.86Nm at 30°/s, 26.7±7.93Nm at 60°/s, and 24.33±6.98Nm at 90°/s in the hybrid-trained limbs. At the 6-week midpoint they had increased, albeit in a statistically insigniﬁcant manner relative to baseline, to 32.08±7.42Nm, 28.75±6.43Nm, and 28.08±7.30Nm, respectively. Progress plateaued and, at the end of the program, flexion torques (32.92±9.54Nm at 30°/s, 30.75±9.58Nm at 60°/s, and 29.58±9.29Nm at 90°/s) differed insignificantly from their baseline values.

Control limbs. Flexion torques in the control limbs were 26.75±5.88Nm at 30°/s, 24.33±5.61Nm at 60°/s, and 22.42±5.35Nm at 90°/s at baseline. At the midpoint of training, they had increased to 30.25±7.23Nm at 30°/s, 28.5±6.26Nm at 60°/s, and 26.75±5.55Nm at 90°/s, respectively, but did not differ signiﬁcantly from their baseline measurements. At the end of training, the torques had further increased to 32.17±9.40Nm at 30°/s, 29.25±8.52Nm at 60°/s, and 27.58±8.10Nm at 90°/s, but the changes remained insignificant (fig 3B).
Fig 3. Muscle force measurements of isometric (A) elbow extension and (B) flexion torque (Nm) at before, 6 weeks, and 12 weeks after exercise were presented, respectively. Muscle force had increased significantly after 12 weeks.
Measurement of Muscle Bulk Using MRI

The triceps and biceps brachii increased in bulk and changed in shape (i.e., each became rounder; fig 4). Changes were pronounced enough to be appreciated visually (fig 5).

**Triceps brachii.** Triceps CSA at the 6-week midpoint of the exercise trial had increased by 16.00% ± 8.39% in the hybrid limbs relative to 1.80% ± 4.14% in the control limbs \((P < .0001)\). At 12 weeks, this discrepancy persisted but had lessened with the triceps CSA 16.20% ± 11.02% in the hybrid trained limbs and 4.25% ± 7.87% in control limbs \((P = .01)\).

**Biceps brachii.** Similar changes occurred in the biceps. At the midpoint of training, the biceps CSA had increased 12.98% ± 8.32%, in the hybrid trained limbs relative to an increase of 7.04% ± 4.15% in the control limbs \((P = .04)\). After 12 weeks, these changes were 16.65% ± 10.74% in the hybrid group relative to a 7.00% ± 4.54% change in control limbs \((P = .005)\).

**DISCUSSION**

This study shows that, at least in this sample of subjects and muscles, this hybrid exercise program produced significantly greater changes in muscle bulk and triceps brachii strength than did a conventional NMES approach. Although our sample size and the muscles studied were limited, these findings deserve further discussion.

First, this approach may offer several advantages. For example, volitional muscle contractions activate slow-twitch and fast-twitch muscle in a sequential manner.\(^9\) NMES, on the other

---

**Fig 4.** Example of the changes revealed by MRI in the CSA of the muscles in the right-hybrid-trained brachium. Note that the CSAs of both muscles increased and became rounded after 6 weeks. (A) Before exercise; (B) 6 weeks after hybrid exercise; and (C) 12 weeks after hybrid exercise.

**Fig 5.** Increased ratio of the CSA of brachial muscles, comparing hybrid exercise with control exercise. It was remarkably greater than that of the control exercise both in biceps and triceps brachii. Abbreviation: W, week.
hand, does not follow this physiologic pattern in that it activates slow-twitch muscle poorly and is most efficient in stimulating fast-twitch muscles.9-11 This nonphysiologic pattern of activation may lead to less effective strengthening and may also contribute to the reluctance of many physicians to accept electric stimulation as a common component of therapeutic muscle strengthening programs. A hybrid exercise technique may obviate some of this concern because of its more physiologic approach of using both volitional and electrically stimulated contractions.

Another potential advantage of this approach is the combination of eccentric contractions and electric stimulation. Westing et al,12 for example, reported that the muscle torque resulting from an electrically stimulated eccentric contraction was 21% to 24% greater than that produced by a voluntary eccentric contraction alone. In addition, Seger and Thorstensson13 compared the effects of electrically stimulated eccentric, isometric, and concentric contractions of the quadriceps at angular velocities similar to those of our study. They found that under similar stimulating conditions, eccentric contractions generated torques about 15% to 25% greater than those produced with isometric contractions and about 30% to 50% greater than the torques resulting from concentric contractions.

The CSA findings are also interesting. Not only were CSA increases significantly greater in the hybrid than in the control limbs at both the midpoint and the conclusion of the exercise program, but the bulk (and the strength) of the triceps brachii increased more than that of the biceps. This pattern may not be surprising, because the biceps is used actively throughout the day, whereas the triceps is used less vigorously. Thus, the triceps might have begun at a lower level of its potential maximum strength than the biceps.14 It is also possible that this discrepancy is an artifact of our study design. The biceps brachii is involved in elbow flexion, but it shares the task with the brachialis.

The hybrid program seems to be safe and well tolerated. All of our subjects attended all 36 sessions of the program. There were no injuries. A few individuals complained of postexercise, delayed-onset muscle soreness early in the program. This was not unexpected because previous reports6 on electric stimulation have noted late-onset muscle soreness, but there is virtually no evidence of damage to the muscles or tendons among people undergoing electrically stimulated muscle strengthening. In addition, our hybrid exercise used considerably lower stimulation intensities than what is typically used in many NMES studies.12,13

Further discussion is warranted about whether this hybrid exercise can be optimized and about its appropriateness for use on other muscles, with elderly patients, or with people with osteoporosis. We plan to continue studying the short- and long-term effects of this exercise approach.

CONCLUSIONS

It appears that the hybrid exercise technique described here is more effective in increasing muscle bulk and strength than is the conventional NMES program we used in this study. As such, it may have a role in musculoskeletal rehabilitation. However, both our sample and the muscles we studied were limited. More research is necessary to establish clear therapeutic benefits and optimal parameter choices.

Acknowledgment: We thank Akira Maeda, MD, Narita Orthopaedic Hospital, Fukuoka City, Fukuoka, Japan for providing access to the MRI device.

References


Suppliers

b. Chattanooga Group Inc. 4717 Adams Rd, Hixson, TN 37343.
c. Hitachi Medical Corp, 1-1-14, Uchikanda, Chiyodaku, Tokyo 101-0047, Japan.
d. SPSS Inc, 233 S Wacker Dr, 11th Fl, Chicago, IL 60606.